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TECHNICAL INFORMATION BULLETIN
89-1

EQUIPMENT LEVEL FALLOUT RADIATION EFFECTS APPROACH

FEBRUARY 10, 1989

OFFICE OF THE MANAGER
NATIONAL COMMUNICATIONS SYSTEM
WASHINGTON, D.C. 20305

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National Security Decision Directive (NSDD) 97 and Executive Order (EO) 12472 call for the ability to maintain National Security Emergency Preparedness (NSEP) communication capabilities in times of national disaster, which includes a nuclear attack. The Office of the Manager, National Communications System (OMNCS) sponsors the Electromagnetic Pulse (EMP) Mitigation Program to evaluate and, where possible, mitigate the effects of the nuclear attack. Fallout radiation has been identified as an environment which may affect the performance of the regional and national telecommunication system. This report presents the investigations in the network level fallout radiation methodology used to determine the effects of this environment. Alternative techniques are presented to improve the methodology.

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TABLE OF CONTENTS

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FOREWORD

The National Communications System (NCS) is an organization of the Federal Government whose membership is comprised of 23 Government entities. Its mission is to assist the President, National Security Council, Office of Science and Technology Policy, and Office of Management and Budget in:

- The exercise of their wartime and non-wartime emergency functions and their planning and oversight responsibilities.

- The coordination of the planning for and provision of National Security/Emergency Preparedness communications for the Federal Government under all circumstances including crisis or emergency.

In support of this mission the NCS has initiated and manages the Electromagnetic Pulse (EMP) Mitigation Program. The objective of this program is the removal of EMP as a significant impediment to timely reestablishment of regional and national telecommunications following an attack against the United States that includes high-altitude nuclear detonations. The program approach involves estimating the effects of High-altitude EMP (HEMP) on telecommunication connectivity and traffic handling capabilities, assessing the impact of available HEMP mitigation alternatives, and developing a comprehensive plan for implementing mitigation alternatives. In addition to studying the effects of HEMP, the program has been expanded to address the effects of fallout radiation on the Public Switched Network (PSN). This report presents alternative techniques for assessing equipment level survivability to Fallout Radiation as applied to the EMP Mitigation Program.

Comments on this TIB are welcome and should be addressed to:

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EXECUTIVE SUMMARY

National Security Decision Directive (NSDD) 97 and Executive Order (E.O.) 12472 call for the ability to maintain National Security Emergency Preparedness (NSEP) communication capabilities in times of national disaster, which includes a nuclear attack. The Office of the Manager, National Communications System (OMNCS) sponsors the Electromagnetic Pulse (EMP) Mitigation Program to evaluate and, where possible, mitigate the effects of the nuclear attack. Fallout radiation has been identified as an environment which may affect the performance of the regional and national telecommunications system. This report presents the investigations in the network level fallout radiation methodology used to determine the effects of this environment. Alternative techniques are presented to improve the methodology.

NETWORK LEVEL FALLOUT RADIATION APPROACH

The Fallout Radiation Effects Methodology approach shown in Exhibit ES-1 employs four modules for analyzing network level fallout radiation effects. The first module, which is the focus of this report, assesses the effects of nuclear radiation on network telecommunications equipment. Module two is the network topology data base, which contains detailed information on network equipment types, locations, and interconnections. The third module is a radiation dispersion model that specifies radiation dosage levels network equipment are exposed to as calculated from the weapon laydown scenario. The fourth module is a computer model that predicts the connectivity of a radiation exposed network based on the results of the first three modules.

The first module predicts equipment level response from piece part survivability data. The steps in this module are shown in Exhibit ES-2. In the first step, the types and quantities of the piece parts that compose the

EXHIBIT ES-1

Fallout Radiation Effects Methodology

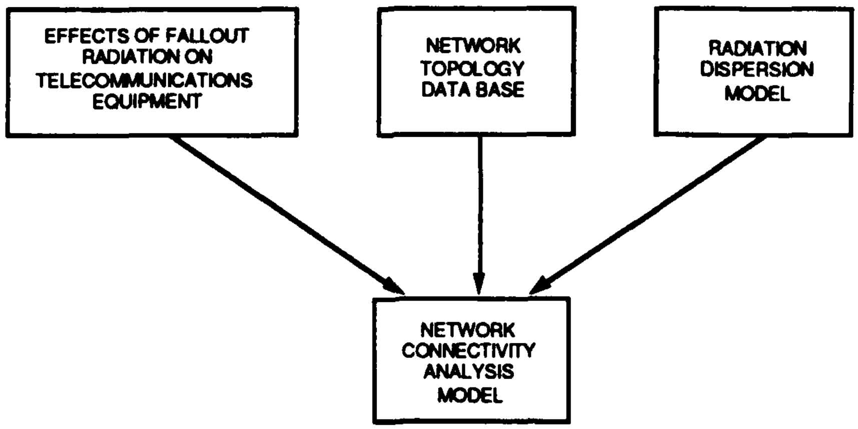
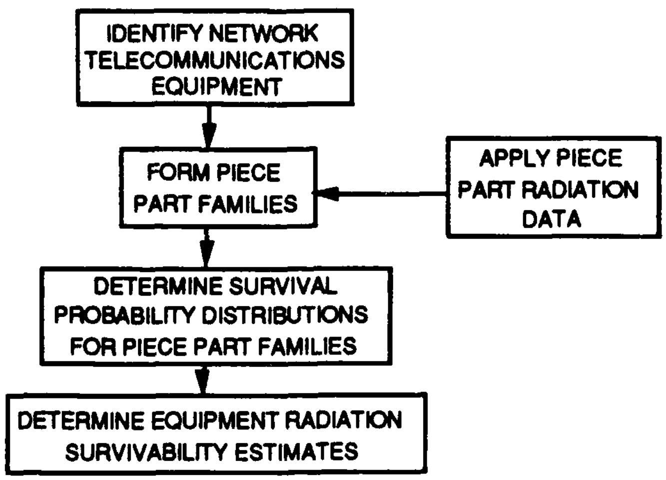


EXHIBIT ES-2

Equipment Survivability Estimation Methodology



telecommunications equipment are identified. In the second step, the piece parts are formed into piece part families. This process is possible because different piece part technologies can exhibit similar response to fallout radiation. The justification for forming piece part families is based on physical properties (manufacturing process, material, etc.) and the available piece part radiation data. In the third step, a unique survival probability distribution is calculated for each piece part family using statistical techniques. Finally, the individual survival probability distributions of the piece part families are used to develop equipment survival probability distribution curves.

SCOPE OF REPORT

This report presents alternative techniques to those presently used in the first module of the Fallout Radiation Effects Methodology. The alternative techniques proposed in this report *make use of limited, available piece part survivability data* in a manner consistent with the goals and resource limitations of the OMNCS EMP Mitigation Program. In this report, the three areas evaluated to assess equipment survivability based on the survivability of its piece parts are as follows:

- Techniques for forming piece part families from individual piece parts
- Techniques for quantifying piece part family survivability
- Techniques for estimating equipment survivability based on device family survivability.

Currently, the "distribution-based" technique is used to form piece part families because it is based on the survivability distributions of the piece part radiation data. In the existing methodology, the radiation data for each piece part family is used in the Bayesian Survivability Model (BSM) to produce piece part family survivability curves. These curves are expressed in cumulative distribution functions (CDFs) and probability density functions

(PDFs), which describe the distribution of survival probabilities for the piece part family. The decision to form piece part families is based on the difference between the PDF standard deviations of the combined piece part data and the separate data.

The alternative technique is called the "Kolmogorov Smirnov" (K-S) technique. This technique uses K-S statistics, which is a nonparametric method of testing hypotheses. The K-S technique uses the raw radiation data on the piece parts to determine if the piece part families have similar distributions. The raw radiation data are the actual results of the radiation tests performed on piece parts. This is done to avoid additional processing of the data, as is done in the current technique when the survivability distributions of the data are used. Such manipulations can lose statistical information and obscure the statistical validity of the results. This technique uses the CDF of the actual piece part radiation data and compares them to observe significant differences. The CDFs generated by the K-S technique represent the probability that there are failure test data at a given radiation level or less. This is not to be confused with the CDFs generated by the distribution-based technique, which represent the distribution of survival probabilities for the piece part family.

The current technique for quantifying piece part family survivability is called the "Bayesian" technique. As stated above, the radiation data for each piece part family is used in the BSM to produce piece part family survivability curves. This technique places equal significance (weighting) on each piece part family included in the equipment, which implies that each family equally affects equipment survivability. The alternative technique is called the "Weighted Binomial" technique. It uses available device performance data and equipment parts lists to estimate the probability distribution for the number of devices failing within the equipment. The resulting family survivability distribution reflects the portion of the equipment type within the network that fail. In the weighted binomial approach, equipment survivability is based on the quantities of each piece part family in the equipment.

The "Survivability of All Piece Part Families" technique is currently used to estimate equipment survivability. It uses a Monte Carlo process to

combine the piece part level performance data to estimate equipment level performance. The alternative technique is called the "Population-Weighted Survivability of Piece Part Families" technique. The survivability curves generated by the Weighted Binomial technique are used to determine equipment level survivability. The alternative technique will provide the additional information about the population of each piece part family in the equipment survivability curves.

CONCLUSIONS

A comparison of the results of the two techniques shows that the K-S based technique is much stricter than the distribution-based technique. The K-S based technique allows only three pairs of piece part families to be combined, leaving 26 individual piece part families. The distribution-based technique allows 17 piece part families to be combined, leaving only 15 piece part families. Although from this initial comparison it may seem that the distribution-based technique is preferrable, the acceptance of a technique should be based on its statistical merits rather than the results. The following data and test statistics are used in each technique:

- BSM Technique
  Data: Distribution Curves generated by BSM.
  Test Statistic: Standard Deviation of Distribution Curves.
- K-S Technique
  Date: Cumulative Distribution Curves from actual test data.
  Test Statistic: Differences between Cumulative Distribution Curves.

The K-S technique is the preferred technique for forming piece part families from individual piece parts. It provides a more statistically rigorous solution than the distribution-based technique.

The preferred technique for quantifying piece part family survivability is dependent on the results of the equipment level estimates of survivability. The current techniques for quantifying piece part family survivability (Bayesian technique) and equipment survivability (Survivability of All Piece Part Families technique) are always used together. The same is true of the

alternative techniques used to predict these same survivabilities. The results using the Population-Weighted Survivability of Piece Part Families technique provides too optimistic a solution. Since the Weighted Binomial technique is used only with this alternative technique for quantifying equipment survivability, it should not be used. Therefore, with the present information, the Bayesian technique is the preferred method for quantifying piece part family survivability.

The preferred technique for estimating equipment level survivability is the Survivability of All Piece Part Families technique. The switch survivability curves generated by the Population-Weighted Survivability of Piece Part Families may be optimistic. This is because the Population-Weighted Survivability of Piece Part Families approach assumes that the survivability of the equipment is dependent on the prevalence of piece part types. In telecommunications equipment, the survivability of the equipment should not be controlled by its strongest link. However, by using population as the sole criteria for survivability, the population of the strongest links in the equipment controls the survivability of the equipment. Although the alternative technique for predicting switch survivability is useful and produces reasonable results, it cannot be used as the sole criteria for survivability. Other parameters, such as the percentage of mission critical piece parts in the equipment, must be used in conjunction with the population factor to determine equipment survivability.

RECOMMENDATIONS

Given the present choices, the recommended overall equipment level fallout radiation approach is as follows:

- K-S technique to form piece part families from individual piece parts
- Bayesian technique to quantify piece part family survivability
- Survivability of All Piece Part Families technique to estimate equipment survivability.

The recommendations for improvements in the methodology are drawn from the conclusions of the analysis. The overall approach stated above is based on available information. However, the techniques not used may still be useful with the proper improvements. The suggested follow-on activities are:

- Increase the radiation data base on the device types used in the equipment. This will allow more families to be combined, and create greater confidence in the results of the K-S technique.
- Determine other weighting factors for the piece part family survivability curves. One area of investigation may be the sensitivity of the switch survivability to the percentage of mission critical piece parts in the equipment. The weighting factors will provide further insight to the response of the equipment to fallout radiation.
- Investigate improvements to the K-S test statistic. One area of investigation may be the distributions of the differences between two CDF curves. This can increase the confidence in the results from the K-S technique.

1.0 INTRODUCTION

National Security Decision Directive (NSDD) 97 and Executive Order (E.O.) 12472 call for the ability to maintain National Security Emergency Preparedness (NSEP) communication capabilities in times of national disaster, which includes a nuclear attack. Electromagnetic pulse (EMP) is a by-product of a nuclear detonation that is characterized by intense, high-frequency electromagnetic fields. The currents induced on telecommunications equipment may be sufficiently severe to damage the telecommunications resources used by critical Government users. Telecommunications equipment are most susceptible to high-altitude EMP (HEMP), which occurs for nuclear detonations at greater than 50 km above the earth's surface -- hence the need for the Office of the Manager, National Communications System (OMNCS) to sponsor the EMP Mitigation Program.

The EMP Mitigation Program analyzes and, where feasible, lessens the degradation effects of HEMP on national telecommunication resources. The program focuses its efforts on the resources of the Public Switched Network (PSN) because it comprises the largest, most diverse set of telecommunication assets in the United States. The PSN is the focus of the National Communications System (NCS) NSEP telecommunication enhancement activities. The majority of NCS member organizations rely on the PSN to conduct their NSEP responsibilities. In addition to studying the effects of HEMP, the program has been expanded to address the effects of fallout radiation on the PSN.

1.1 BACKGROUND

The PSN is a vast, complex, commercial resource. It encompasses the entire nation with sophisticated equipment, and is continually changing with the implementation of new technologies. Since the PSN is composed of private companies, the OMNCS has little direct control over its operation and the equipment it employs. These issues are dictated by the commercial

marketplace. Due to proprietary concerns, it is not possible for the Government to have complete information regarding the structure and operation of the commercial carrier networks. While the lack of complete data makes it difficult to assess the effects of HEMP and fallout radiation on the PSN, the OMNCS believes that preliminary HEMP and fallout radiation effects estimations on the PSN can be conducted using the data available. These estimates can be useful for developing long-range HEMP and fallout radiation initiatives.

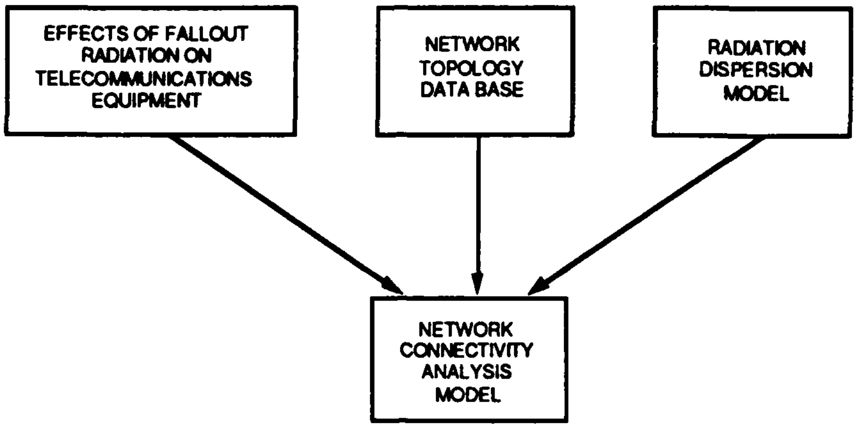
The EMP Mitigation Program uses an evolutionary process to continually improve its understanding of HEMP effects on the PSN. The basis for the analyses is test data regarding the survivability of individual switches and transmission facilities. This survivability information, combined with knowledge of the network topology and threat, is used to estimate post-attack connectivity at the network level. The key phrase is "network level," because the OMNCS is concerned with national communication capabilities. These capabilities cannot be determined by only analyzing the individual network equipment -- the entire network must be assessed.

Like HEMP, fallout radiation is a by-product of a nuclear detonation and is a potential threat to the survivability of network resources. It is the residual radiation left following a blast that can be carried by wind and rain to locations far from the weapon detonation point. A method to assess the survivability of telecommunications equipment subjected to fallout radiation based on the survivability of the equipment's piece parts has been proposed. This method was developed from the OMNCS need to provide a technically sound and cost-effective method to support decisions concerning fallout radiation effects on NSEP telecommunications performance.

1.2 NETWORK LEVEL FALLOUT RADIATION APPROACH

The Fallout Radiation Effects Methodology approach shown in Exhibit 1 (Reference 1) employs four modules for analyzing network level

EXHIBIT 1-1
Fallout Radiation Effects Methodology

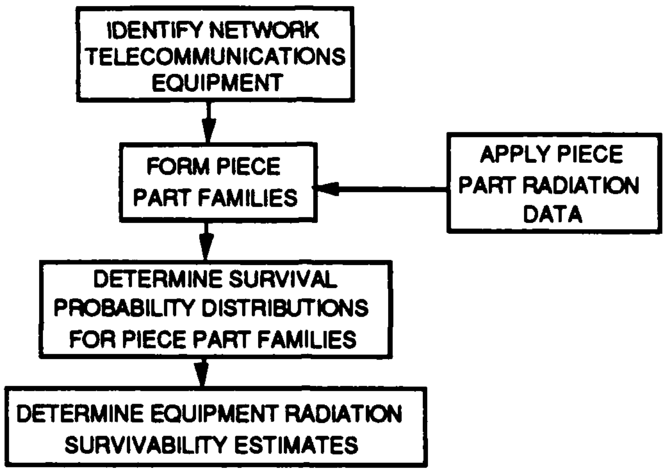


fallout radiation effects. The first module, which is the focus of this report, assesses the effects of nuclear radiation on network telecommunications equipment. Module two is the network topology data base, which contains detailed information on network equipment types, locations, and interconnections. The third module is a radiation dispersion model that specifies radiation dosage levels network equipment are exposed to as calculated from the weapon laydown scenario. The fourth module is a computer module that predicts the connectivity of a radiation-exposed network based on the results of the first three modules.

The first module predicts equipment level response from piece part survivability data. The steps in this module are shown in Exhibit 1-2. In the first step, the types and quantities of the piece parts that compose the telecommunications equipment are identified. In the second step, the piece parts are formed into piece part families. This process is possible because different piece part technologies can exhibit similar response to fallout radiation. The justification for forming piece part families is based on physical properties (manufacturing process, material, etc.) and the available piece part radiation data. In the third step, a unique survival probability distribution is calculated for each piece part family using statistical techniques.

EXHIBIT 1-2

Equipment Survivability Estimation Methodology



Finally, the individual survival probability distributions of the piece part families are used to develop equipment survival probability distribution curves.

1.3 PURPOSE

The purpose of this report is to present alternative techniques to those presently used in the first module of the Fallout Radiation Effects Methodology. The alternative techniques proposed in this report *make use of limited, available piece part survivability data* in a manner consistent with the goals and resource limitations of the OMNCS EMP Mitigation Program. In this report, the three areas evaluated to assess equipment survivability based on the survivability of its piece parts are as follows:

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The alternative technique is called the "Kolmogrov Smirnov" (K-S) technique. This technique uses K-S statistics, which is a nonparametric method of testing hypotheses (Reference 3). The K-S technique uses the raw radiation data on the piece parts to determine if the piece part families have similar distributions. The raw radiation data are the actual results of the radiation tests performed on piece parts. This is done to avoid additional processing of the data, as is done in the current technique when the survivability distributions of the data are used. Such manipulations can lose statistical information and obscure the statistical validity of the results. This technique uses the CDF of the actual piece part radiation data and compares them to observe significant differences. The CDFs generated by the K-S technique represent the probability that there are failure test data at a given radiation level or less. This is not to be confused with the CDFs generated by the distribution-based technique, which represent the distribution of survival probabilities for the piece part family.

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the network that fail. In the weighted binomial approach, equipment survivability is based on the quantities of each piece part family in the equipment.

The "Survivability of All Piece Part Families" technique is currently used to estimate equipment survivability. It uses a Monte Carlo process to combine the piece part level performance data to estimate equipment level performance. The alternative technique is called the "Population-Weighted Survivability of Piece Part Families" technique. The survivability curves generated by the Weighted Binomial technique are used to determine equipment level survivability. The alternative technique will provide the additional information about the population of each piece part family in the equipment survivability curves.

In this analysis, the assumed fallout radiation levels that equipment are exposed to are not chosen with respect to any particular fallout radiation pattern. The radiation levels have been arbitrarily selected to illustrate statistical modeling tools to quantify fallout radiation survivability. In addition, the expected fallout radiation levels do not take into account any building or equipment shielding effects.

1.4 ORGANIZATION

This report is organized to present the reasoning and implementation of each alternative technique proposed. The next three sections describe the details of the proposed alternative techniques. A simple example using piece part radiation data collected for the 5ESS switch is given to illustrate the alternative techniques. A comparsion is made between the alternative and current techniques. Section 5.0 states the conclusions drawn from these comparisons. It identifies the present set of techniques that should be used to quantify equipment level Fallout Radiation effects. Recommendations for future efforts in the Network Level Fallout Radiation Methodology are also presented in Section 5.0.

2.0 TECHNIQUES FOR FORMING PIECE PART FAMILIES FROM INDIVIDUAL PIECE PARTS

A preliminary equipment level survivability prediction can be obtained from the limited radiation information on piece parts and the knowledge of the device types in the equipment. The piece parts are grouped into piece part families when technically and statistically possible. The justification for forming piece part families is that some piece parts exhibit similar responses to fallout radiation.

This section explains the reasoning for the OMNCS approach to combining piece part data into piece part families. The limitations of PSN equipment data are discussed to identify the benefits of grouping similiar piece parts into families. The current distribution-based technique for grouping piece parts is presented along with the proposed alternative Kolmogorov Smirnov (K-S) technique. An example of the K-S technique is presented using the stock available data on the 5ESS switch. This section concludes with a technical discussion of the two techniques.

2.1 AVAILABLE PIECE PART DATA FOR ANALYSIS

To understand the two techniques used to combine data, a description of available test data is necessary. A major limitation of the statistical characterization of equipment performance to fallout radiation is the lack of sufficient piece part fallout radiation performance data. The sample sizes of the radiation piece part test data tend to be small and are often available for only a small number of piece part types. Furthermore, the data have been collected under a variety of test conditions.

The data available for this analysis are generated from the study of the 5ESS Radiation Hardness Assessment Program (RHAP) (Reference 4). The piece part fallout radiation test data gathered in the 5ESS RHAP were collected from the following sources in the radiation community:

- U.S. Army Harry Diamond Laboratories (HDL) Component Response Information Center (CRIC)
- Defense Atomic Support Agency Information Analysis Center (DASIAC) Electronics Radiation Response Information Center (ERRIC)
- NASA Jet Propulsion Laboratory
- Institute for Electrical and Electronics Engineers (IEEE) Transactions on Nuclear Science.

These data bases were developed from data gathered from independent sources, each of which has individual goals and objectives.

Fifty-two piece part families have been identified in the 5ESS RHAP final report. The list of families that have radiation test data are shown in Exhibit 2-1, including the number of test samples. No data were identified for the remaining twenty-three families defined. The sample size is assumed to be one in cases when the RHAP data base does not indicate a sample size. In the RHAP, radiation failure levels for a number of piece parts are determined from actual test data on the particular piece part. However, piece parts without actual test data have assigned radiation failure levels corresponding to actual test data from similar devices. Data obtained in this manner are not used in this analysis because they are not valid raw test data.

One measure of confidence in the available data is the variation in the data among the different sources described. The three most significant types of variations in the piece part response to radiation are inherent, experimental, and interpretation.

Inherent variations in radiation response of piece parts can result from differences between lots and vendors. In commercial piece parts, lot-to-lot variations are produced by differences in the processing parameters during the fabrication of a piece part manufactured by the same vendor. Although processing parameters are controlled closely enough to produce an electrically functioning piece part, they may not be controlled closely enough to produce piece parts that are uniformly sensitive to radiation. The restrictions on the electrical parameters of a piece part may be met differently by different manufacturers, thereby allowing different radiation responses from

EXHIBIT 2-1

Initial Technology Families

Piece-Part Family	Test Sample Size
Diode	13
Bipolar Transistor	13
Bipolar Digital - ALSTTL	49
Bipolar Digital - ECL	6
Bipolar Digital - FTTL	89
Bipolar Digital - IMOX	11
Bipolar Digital - LSTTL	199
Bipolar Digital - OXIL	13
Bipolar Digital - STTL	23
Bipolar Digital - TTL	6
Bipolar Linear - CBIC	1
Bipolar Linear - Driver/Receiver	17
Bipolar Linear - Op-Amp	86
Bipolar Linear - Timer	10
Bipolar Linear - Voltage Regulator	6
CMOS Analog - A/D Converter	5
CMOS Analog - Switch/Mux	17
CMOS Digital - 4k/16k SRAM	130
CMOS Digital - CD4000	55
CMOS Digital - 54HC	19
CMOS Digital - CHMOS II	11
NMOS Digital - AT&T NMOS	1
NMOS Digital - 8k/16k SRAM	14
NMOS Digital - 4k SRAM	26
NMOS Digital - DRAM	41
NMOS Digital - HMOS I	264
NMOS Digital - HMOS II	143
NMOS Digital - Misc.	41
NMOS Digital - UVEPROM	128

electrically similar piece parts. Vendor-to-vendor variations are caused by differences among the processing methods used by the vendors to fabricate piece parts. The radiation failure threshold of standard commercial piece parts with inherent variations may vary by more than an order of magnitude, making the exact prediction of the radiation failure threshold difficult.

Experimental variations include differences in test data format, test data age, parameters tested, temperature of the radiation test environment, and radiation exposure (dose) rate. Further details on experimental variations can be found in Reference 5.

Interpretation variations occur in piece part assessments because the data are obtained from a variety of programs with independent goals and objectives. Typically, several parameters contribute to interpretation variations, the data statistics generated (e.g., mean, lowest failure level, etc.), the differences between manufacturer specifications and designer specifications, and the distinction between piece part degradation and piece part failure.

In addition to variations in the data, there is also uncertainty in the piece parts in the system. Without detailed information on how the piece parts are used within circuits, the susceptibility of the equipment to fallout radiation is difficult to predict. When comprehensive data are not available, the conservative approach to assessing equipment survivability is to assume that all piece part technologies are critical.

2.2 DISTRIBUTION-BASED TECHNIQUE

Due to limited data, the piece parts are formed into piece part families to provide larger (statistically significant) sample sizes in the distribution-based technique. These families are collections of devices that use similar semiconductor technologies, and are expected to exhibit similar radiation response characteristics. The piece part families are formed based on fundamental physical properties (e.g., manufacturing process, material, etc.) of the piece parts.

The technique uses the PDF survivability curves generated by the BSM to determine if families should be combined. These curves show the distribution of the survival for the piece part family. The technique compares the standard deviations for the various distributions. A decrease in standard deviation implies greater confidence that the piece parts are similar. The data used consist of the original piece part families that were formed using basic physical properties. After combining piece parts into new piece part families, the standard deviations of the new families are calculated. The new standard deviations are compared to the standard deviations of the original families. Combining technology families with similar distributions decreases the standard deviation of the PDF curve. Likewise, combining technology families with dissimilar distributions increases the standard deviation of the PDF curve.

The distribution-based technique assumes that a ten percent decrease in the standard deviation indicates distributions are sufficiently similar to warrant grouping families. When there are limited data, the piece part families created are preliminary. As more data become available, it is possible that different piece part families may be formed.

2.3 K-S BASED TECHNIQUE

The distribution-based technique provides a baseline for grouping test data, but the technique lacks statistical rigor without statistical proof of the method used. In addition, the method uses data that have been modified by the BSM, which can obscure the data's statistical accuracy. The alternative technique is the K-S based technique. The Kolmogorov-Smirnov statistical technique is one of a group of nonparametric methods that tests statistical hypotheses. Nonparametric methods are not concerned with testing or estimating the parameters of interest, nor do they require knowledge of how the parameters of interest are distributed. The K-S statistical method is a technique for finding a confidence band for comparing CDFs. The maximum difference "D" between the two functions is used to construct the confidence

band. The statistic D can be used to test the hypothesis that two random samples came from the same population.

The K-S technique uses raw radiation data instead of data processed by the BSM. It tests the hypothesis that the distributions of two data sets are from the same distribution. The raw radiation data are the actual test results of the radiation tests performed on piece parts. Sample results using the K-S technique are shown in Exhibit 2-2. The raw data are used to generate discrete CDF curves, by determining the percentage of devices that failed up to a given dose level. This percentage is the CDF value for that dose level. Statistics dictate that at the highest dose level tested for each piece part family, the CDF converges to unity. This indicates that 100 percent of the devices tested failed at that dose level or lower. The K-S technique assumes that the measured data accurately reflect the true CDF curve. The CDF curves are therefore made up of step functions of various heights.

The K-S technique calculates the largest difference between the CDFs of the two families. This difference (the D statistic) is used as the test statistic to determine if the hypothesis can be accepted. A maximum allowed difference is determined from the sample size, the knowledge of the distribution of allowable differences, and the confidence level. If the largest calculated D is less than the maximum allowable difference, the hypothesis is accepted and the two distributions are concluded to be the same. Otherwise, the hypothesis is rejected and the two distributions are concluded to be different. Therefore, small D values tend to support the merging of data.

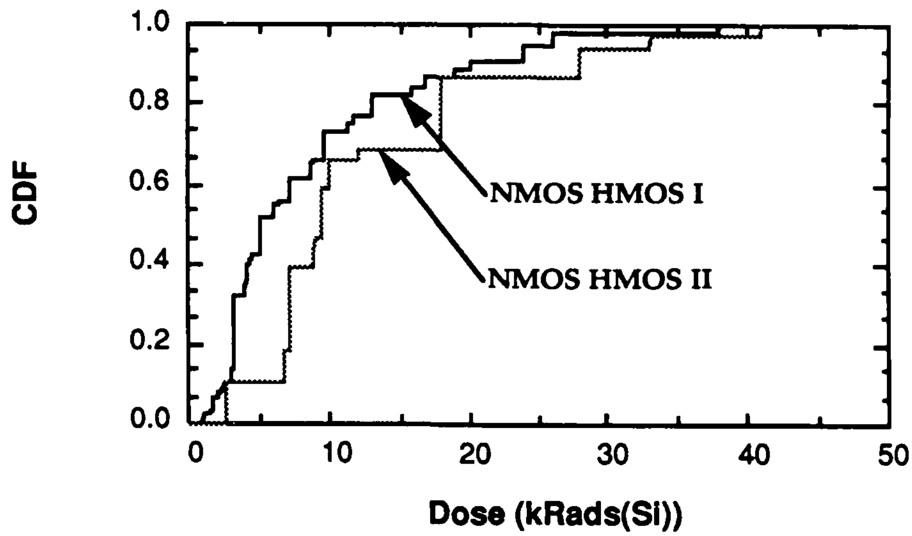
The maximum allowable difference increases with an increase in confidence. To understand this result, it is necessary to understand the basis of testing hypotheses. The following are the four possible results of a hypothesis test:

- Hypothesis concluded true, hypothesis actually true
- Hypothesis concluded true, hypothesis actually false
- Hypothesis concluded false, hypothesis actually false
- Hypothesis concluded false, hypothesis actually true.

The confidence level indicates the probability of the first result. However, this probability does not indicate the probability of the second result, which is really of interest. It is important to know how often an error

EXHIBIT 2-2

Comparing Two Piece Part CDF Failure Curves



is made in the conclusion drawn from the test data. The probability of the last result is just one minus the confidence. This indicates how often an error is made when the conclusion is the hypothesis is false.

This decision is best illustrated by an example. The hypothesis to be tested is that the group of light bulbs has a lifetime of at least X hours. To increase the confidence that the hypothesis is accepted when a sample of light bulbs are tested, the assumed lifetime (X) is decreased. Although the decrease in X will increase the acceptance of the hypothesis, there is no indication of how often the sample test gives the incorrect conclusion (second result). The confidence level does indicate how often an incorrect conclusion is made when the sample test gives the conclusion that the lifetime is less than the hypothesized one (fourth result). This is because the confidence level predetermines the percentage of the time the results of a sample test indicate the lifetime is less than the hypothesis when the lifetime is the hypothesis value. The K-S technique really calculates the probability of error when the conclusion is made that the distributions are different. The goal is to minimize this error.

The present K-S hypothesis assumes that the distributions are the same. The hypothesis can not be that the distributions are different because it is impossible to prove unless all the data in the population are collected. The present hypothesis (same distribution) depends on data showing a difference to disprove the hypothesis. However, the alternative hypothesis (different distribution) depends on data showing no difference to disprove the hypothesis. This is a very difficult task because, even if all data collected are identical, it is possible the next data point collected will be different.

2.4 ILLUSTRATION OF THE DISTRIBUTION-BASED TECHNIQUE FOR COMBINING PIECE PART DATA

The uncertainty in the collected data can be great enough to prohibit distinguishing between the radiation responses of certain piece parts. The lack of discrimination means that more piece part data may be combined without a loss of information. Therefore, some of the original piece part families may be combined. However, not all piece part families with similar survivability distributions can be grouped. It is recognized that some vastly different technologies might coincidentally exhibit similar distributions due to a limited amount of data points. For example, if CMOS and Bipolar piece part families exhibit similar distributions, the families are not combined because of the dissimilarities in the device families. Therefore, grouping can only be performed if the technology and the survival distributions are similar. Exhibit 2-3 presents the new piece part families generated using the distribution-based technique. Fifteen piece part families are formed from the twenty-nine original piece part families.

2.5 ILLUSTRATION OF THE K-S BASED TECHNIQUE FOR COMBINING PIECE PART DATA

The same families that were compared in Reference 6 are also compared in this report to contrast the two techniques. All the compared

EXHIBIT 2-3

New Technology Families from Distribution-Based Technique

Piece-Part Family

Bipolar Digital -	ALSTTL
Bipolar Digital -	FTTL
Bipolar Digital -	IMOX
Bipolar Digital -	LSTTL
Bipolar Digital -	OXIL
Bipolar Linear -	Driver/Receiver, CBIC
Bipolar Linear -	Op-Amp, Timer, Voltage Regulator
CMOS Analog -	A/D Converter, Analog Switch/MUX
CMOS Digital -	4k/16k SRAM
CMOS Digital -	CD4000
CMOS Digital -	54HC
CMOS Digital -	CHMOS II
NMOS Digital -	AT&T NMOS
NMOS Digital -	8k/16k SRAM, 4k SRAM, DRAM, UVEPROM, Misc. NMOS
NMOS Digital -	HMOS I, HMOS II

families are believed to be technically similar enough to allow combining. The results of the K-S test are given in Exhibit 2-4. The compared families are listed in the first two columns. The third column is the largest difference (Calc. D) determined from the CDF curves. The fourth column is the maximum-allowed difference (Max. D). The confidence level used in the calculations is 99 percent. The 99 percent confidence indicates how often Calc. D will be less than Max. D, given the distributions are truly the same. Therefore, there is only a one percent probability of error when Calc. D is greater than Max. D, and the conclusion is the distributions are different. In other words, the families determined to be different are very likely to be different, given the limited data.

EXHIBIT 2-5a

NMOS HMOS I/NMOS HMOS II CDF Curves

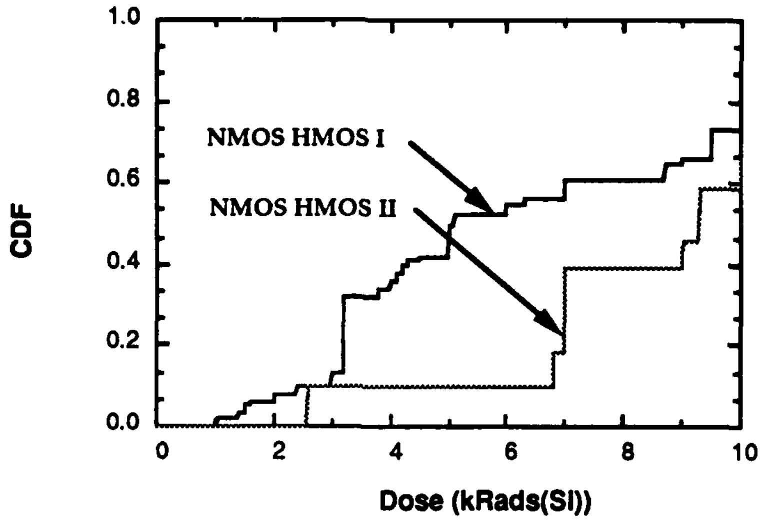
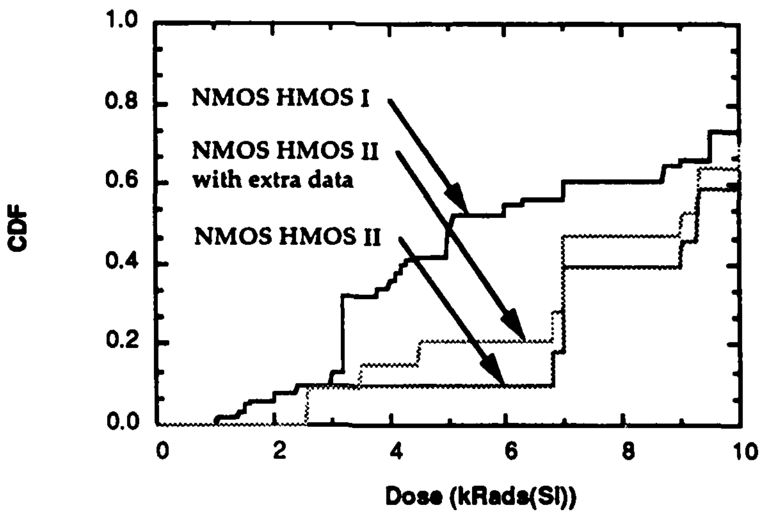


EXHIBIT 2-5b

NMOS HMOS I/NMOS HMOS II CDF Curves with Additional Sample Size



3.0 TECHNIQUES FOR QUANTIFYING PIECE PART FAMILY SURVIVABILITY

A statistical model must be developed to quantify the piece part family survivability from the available data. The model can be used to estimate the equipment level survivability. The results of the model are dependent on the piece part radiation data and technique used to process the data.

The OMNCS is best served by a statistical characterization that adequately describes the performance of all network equipment. The ideal statistical model would include all of the parameters that affect the relationship between piece part performance and equipment performance. These parameters include:

- The number of piece parts from a family present in the equipment
- The functions performed by the piece parts
- The operating conditions (circuit parameters) of the piece parts
- The level of redundancy in the equipment.

Initial discussions with telecommunication equipment vendors indicate that it may be possible for the OMNCS to obtain complete parts lists for "typical" equipment. The term typical is used because a significant portion of telecommunications equipment are semi-custom designs, where each installation is unique. Thus, parts lists are only general indications of actual parts complements. The other three items of information identified above are considered proprietary, and therefore are not available to the OMNCS.

This section reviews the manner in which the statistical model of the piece part family survivability was predicted by the current Bayesian and alternative Weighted Binomial techniques. The assumptions made and data used in both techniques are given. A hypothetical example of the Weighted Binomial technique is presented using the limited available data on the 5ESS switch. An evaluation of each of the two techniques is also provided.

3.1 BAYESIAN TECHNIQUE

Once the piece parts have been identified and grouped into families, a statistical model is required to estimate the impact of piece part performance on equipment performance. The Bayesian technique assumes that all technology families are equally represented in the equipment, and the performance of each family is critical to successful equipment operation. The Bayesian technique uses the available radiation test data, which has been formed into piece part families by either the distribution based or K-S based techniques described in Section 2.0.

The generation of a statistical model for the piece part family survival probability is based on a Bayesian statistical interpretation of component radiation hardness test data. The BSM develops density and distribution curves to estimate technology survivability. The inputs to the model are fallout radiation test data and a noninformative prior distribution. The results are CDF and PDF survivability curves, which describe the probability of the probability of survival for the device family. Exhibits 3-1a and 3-1b are examples of the CDF and PDF curves generated by the Bayesian technique. The value of the CDF at any point "P" is equal to the likelihood that the probability of survival is less than or equal to "P." For example, in Exhibit 3-1a, a CDF value of 50 percent corresponds to a probability of survival of 0.95. Therefore, there is a 50 percent likelihood that the probability of survival is less than or equal to 0.95. The significance of the PDF curve is the area under any x-axis (probability of survival) interval of the curve indicates the likelihood that the probability of survival is within that x-axis interval. Referring to Exhibit 3-1b, an integration of the PDF curve for probability of survival values between 0.90 and 0.95 is equal to 0.75. Therefore, there is a 75 percent likelihood that the probability of survival is between 0.90 and 0.95.

EXHIBIT 3-1a

CDF Survival Curve for 4k/16k SRAM, 500-1000 Rads(Si) Bin

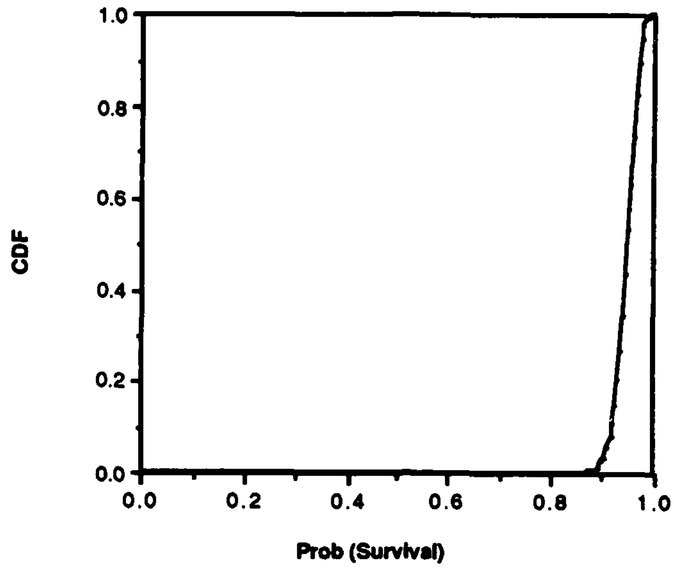
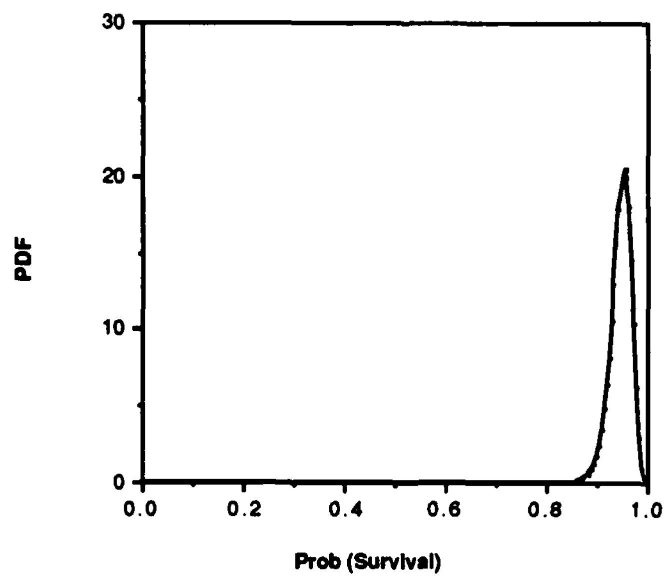


EXHIBIT 3-1b

PDF Survival Curve for 4k/16k SRAM, 500-1000 Rads(Si) Bin



3.2 WEIGHTED BINOMIAL TECHNIQUE

The Weighted Binomial technique expands on the Bayesian technique by including the population of the piece part families in the statistical model. The different piece part families are not assumed to be of equal importance; rather, the importance of each piece part family to equipment survivability is proportional to the prevalence of each piece part in the equipment. The logic behind this approach is that a failure in a piece part family used more frequently in an equipment is more likely to cause the equipment to fail. It is assumed that the percentage of the total number of *piece parts* that fail is the percentage of the *equipment* that fail. This approach yields an equipment survivability probability equaling the survival rates of its piece parts.

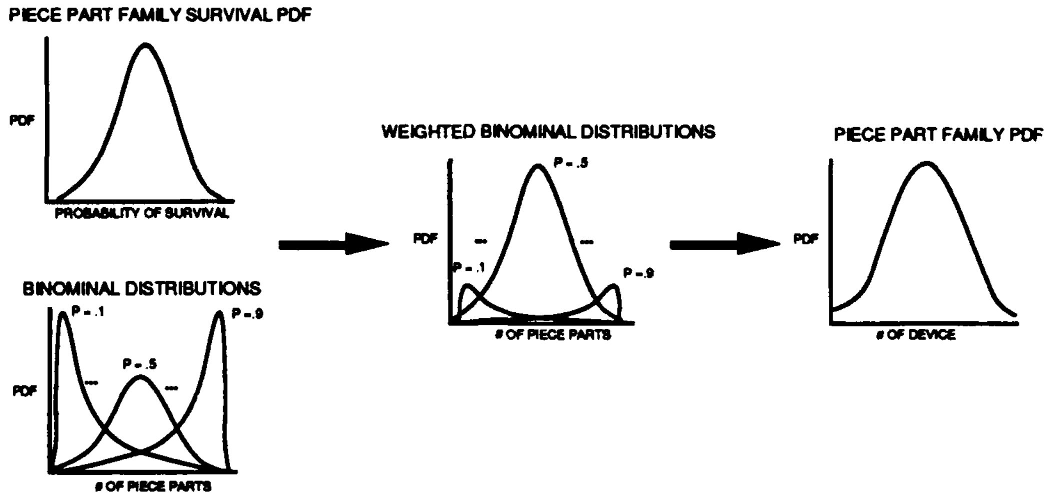
To include the piece part population information in the piece part family survivability curves, it is necessary to predict the probability that a given number of piece parts will survive. The results from the Weighted Binomial technique quantify the expected failure rates for a piece part family, based on a sum of Binomial distributions weighted by the appropriate PDF values for the probability of survival generated by the BSM.

An example of the Weighted Binomial technique is illustrated in Exhibit 3-2. The first step is generating the device family PDF curve and the Binomial distribution curves, shown on the left side of the exhibit. The PDF curve is generated by the BSM in a manner similar to that used in the Bayesian technique. Individual Binomial distribution curves are calculated for survival probabilities ranging from P=0 to P=1. Three typical curves are shown in the exhibit. The Binomial distribution represents the likelihood that the specified number of devices out of the entire population of devices fail, given the selected probability of survival from the BSM generated curves.

The second step in the Weighted Binomial technique combines the curves generated in the first step. Each of the Binomial distribution curves is weighted (scaled) by the value of the PDF curve corresponding to the

EXHIBIT 3-2

Example of Weighted Binomial Technique



probability of survival used for that Binomial distribution curve. For example, the P=0.1 Binomial distribution curve is weighted by the value of the PDF curve corresponding to P=0.1. The result of this step is a group of weighted Binomial distribution curves, as indicated in the middle of the exhibit.

The third step in the Weighted Binomial technique is the generation of a piece part family survivability curve describing the probability that a specified number of the piece parts survive. This curve is illustrated on the right side of the exhibit. The probability that a specified number of devices will survive is equal to the sum of the weighted Binomial distributions that correspond to that number of devices. The result is an overall piece part survivability curve that can be used to estimate equipment survivability. Appendix A contains the detailed mathematics and a description of the Weighted Binomial technique.

3.3 APPLICATION USING THE WEIGHTED BINOMIAL TECHNIQUE

A simple example of the Weighted Binomial technique is applied to the data collected for the 5ESS RHAP. Currently, the actual population of each piece part type in the 5ESS is not available, but the 5ESS RHAP does identify the number of different piece part types (e.g., 54LS00, 8085, etc.). Therefore, the population of each piece part family is assumed to be the number of unique piece part types, instead of the actual number of piece parts in the 5ESS. The CDF and PDF survivability curves for the CMOS CD4000 piece part family are shown in Exhibits 3-3a and 3-3b. The population of the CD4000 piece parts is assumed to be 17, as identified in the 5ESS RHAP. The curves are defined for 5, 50, and 100 kRads(Si). Each curve represents the probability that a number of survivals will be observed at the given radiation dose level. The curves indicate the higher the radiation experienced by the CD4000 piece part family, the higher the probability that less devices survive, which is in line with intuition.

EXHIBIT 3-3a

CDF Survivability Curves for CMOS CD4000 Piece Part Family

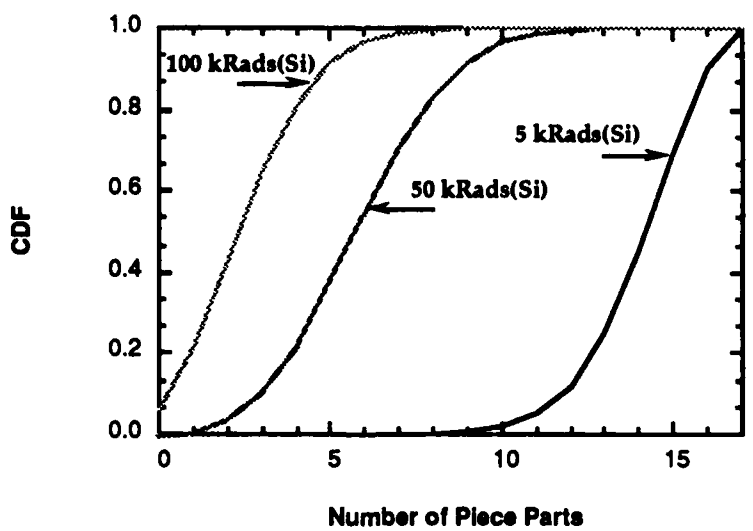
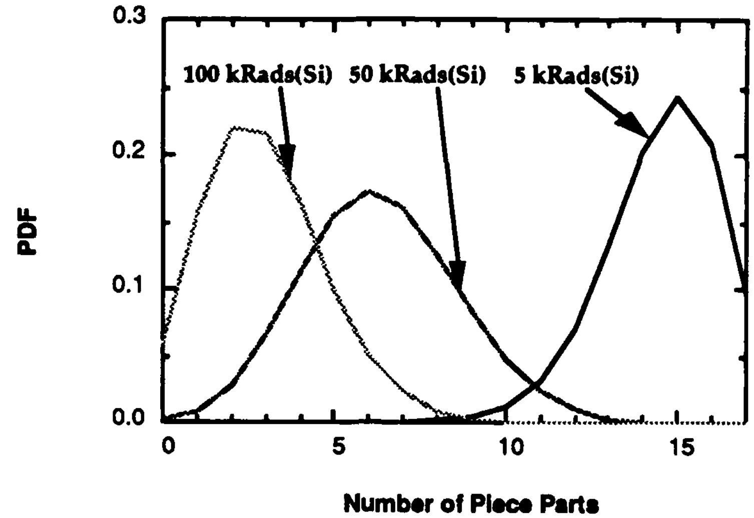


EXHIBIT 3-3b

PDF Survivability Curves for CMOS CD4000 Piece Part Family



3.4 DISCUSSION

A comparison of the Bayesian and Weighted Binomial techniques is difficult because they represent two completely different ways of quantifying the piece part family survivability curves. Although the Weighted Binomial technique has additional information (population of piece part family) included in the statistical model, it may provide too optimistic a solution. For example, piece parts that are critical to system operation, but which are used in very small numbers in each system (e.g., microprocessors) are not given sufficient weighting in this method. However, piece parts that are used quite extensively -- possibly nonessential components (e.g., diodes) -- are weighted too heavily. The evaluation of the two techniques will depend on the equipment level survivability results generated by the two statistical models. These results must be verified to ensure that realistic results are obtained.

4.0 TECHNIQUES FOR QUANTIFYING EQUIPMENT SURVIVABILITY

The final step in determining the equipment level survivability is using the piece part family survivability information to estimate equipment level survivability. The individual survivability curves for each piece part family are used to estimate the survivability of the switch to various fallout radiation levels. The equipment level survivability curve can then be used in the Network Connectivity Analysis Model (NCAM) to predict the survivability of the network.

This section reviews the survivability curves generated by the current Survivability of All Piece Part Families and alternative Population-Weighted Survivability of Piece Part Families techniques. The assumptions and limitations of both techniques are described. A simple example using the Population-Weighted Survivability technique is presented using the limited available data on the 5ESS switch. A comparison is made between the Survivability of All Piece Part Families and the Population-Weighted Survivability techniques.

4.1 SURVIVABILITY OF ALL PIECE PART FAMILIES TECHNIQUE

The Survivability of All Piece Part Families technique assumes that all piece part families are of equal and critical importance in the equipment. The survival of the equipment is dependent on the survivability of all the piece part families in the equipment. Therefore, the probability of equipment survival is the product of the probability of each piece part family surviving. This technique assumes that piece part families that always survive at a very high fallout radiation dose (two orders of magnitude) compared to the dose of interest have a survival probability of one. Therefore, these piece part families are not included in the product.

The Survivability of All Piece Part Families technique uses the survivability curves generated by the BSM. The probability of survival for each piece part family is randomly selected from its CDF curve. The

probability of survival for the equipment is the product of the individual probabilities determined. This calculation can be considered as one possible value in the probability of survival curve for the equipment. The multiplication of piece part family survival probabilities is performed numerous times, in a Monte Carlo process, yielding the distribution of the equipment survivability curve.

Examples of this technique are presented in Exhibits 4-1a, 4-1b, and 4-1c, at three different fallout radiation levels. A characteristic of the Monte Carlo procedure is the number of runs and the sample size determine the smoothness of the curve. A wide variance, resulting from a small sample size of one or more piece part families, increases the jaggedness of the curves. Larger numbers of trials will yield a more complete distribution, and hence decrease the jaggedness of the curve. The jaggedness seen in Exhibits 4-1a and 4-1b is due to the limited data in the AT&T NMOS family. Exhibit 4-1c shows that the switch survivability rapidly decreases at 5 kRads (Si). This is due to the failures in the HMOS piece part family. In this technique, the failures in any single piece part family dominate the probability of survival for the equipment.

4.2 POPULATION-WEIGHTED SURVIVABILITY OF PIECE PART FAMILIES TECHNIQUE

The Population-Weighted Survivability of Piece Part Families technique uses the population of each piece part family to determine the equipment survivability. The Weighted Binomial technique factors in the population of each piece part family in generating the equipment survivability curves. Exhibit 4-2 presents a graphic representation of the Population-Weighted Survivability of Piece Part Families technique. The mathematical details and proofs for this technique are presented in Appendix B.

EXHIBIT 4-1a

PDF Survival Curve for the 5ESS Switch, 500 Rads(Si) Bin

(based on limited data and current technique)

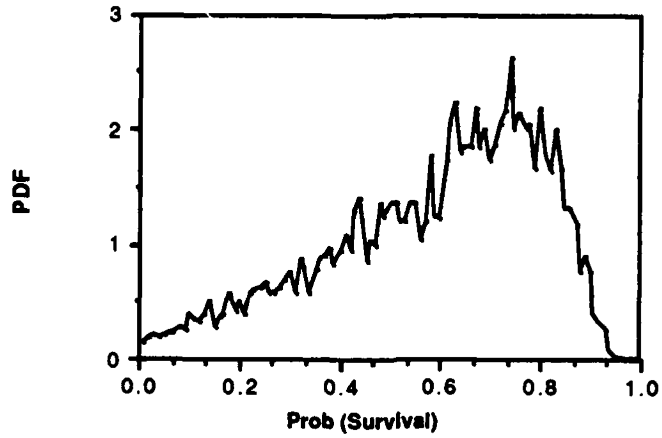


EXHIBIT 4-1b

PDF Survival Curve for the 5ESS Switch, 1 kRads(Si) Bin

(based on limited data and current technique)

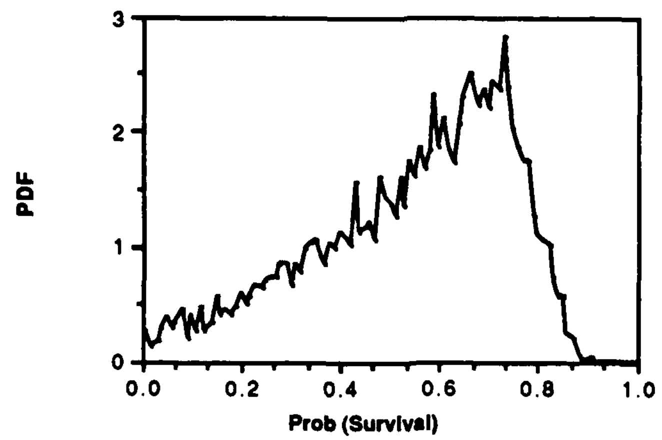
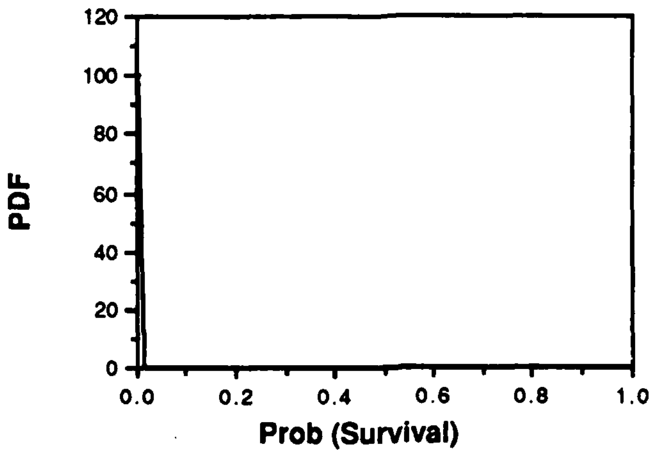


EXHIBIT 4-1c

PDF Survival Curve for the 5ESS Switch, 5 kRads(Si) Bin

(based on limited data and current technique)

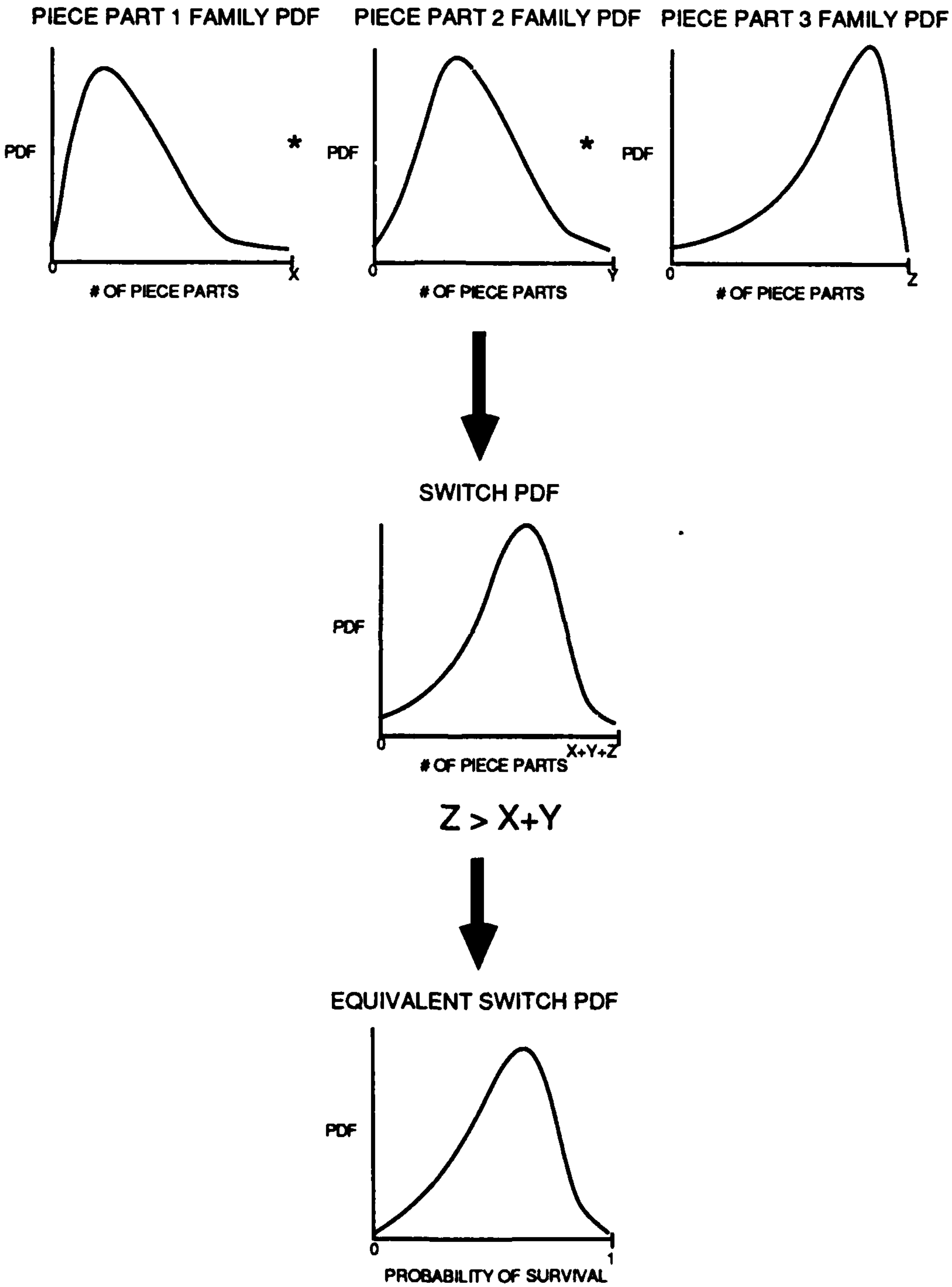


However, the Weighted Binomial technique generated piece part family survivability curves to predict the probability of the number of piece parts in the family that survive. An intermediate step must be taken before the individual piece part family survivability curves can be used to estimate equipment survivability. This step generates a switch survivability curve that predicts the probability of survival for any number of piece parts in the switch. The transformation process to obtain survivability values between 0 and 1 is necessary to accommodate the format used in the NCAM model.

To understand how to generate this intermediate curve, it is instructive to look at a case where there are only two piece part families in the equipment. If there are X and Y piece parts in the part families, there is a total of X+Y piece parts in the equipment. Therefore, the probability that Z piece parts in the equipment survive is the sum of the probability that N devices survive in family one and Z-N piece parts survive in family two, where N has values from 0 to X+Y piece parts. This is expressed in Equation 4-1.

EXHIBIT 4-2

Example of the Switch Survivability Technique



$$(4\text{-}1) \qquad \text{Probability}(Z) = \sum_{N=0}^{X+Y} \text{Probability}_1(N) * \text{Probability}_2(Z-N)$$

The form of Equation 4-1 is the expression for a discrete convolution. It can be shown that with multiple piece part families, the equipment survivability curve is defined as the multiple convolution of the device survivability curves. The intermediate survivability curve can be generated using a multiple convolution. This convolution is the first step shown in Exhibit 4-2 by the convolution of the three piece part families into an equipment population survivability curve.

The next step is to change the x-axis value for which the intermediate survivability curve is defined. This is done by reversing the Weighted Binomial procedure that is used to calculate the survivability curves for the piece part families. Although this is the most straightforward way to change the variable, it assumes that there is a unique solution for the switch survivability curve, which may not be the case. To avoid this problem, a least square fit method is used to find the best equipment survival probability curve that generates the equipment population survival curve. The second step in Exhibit 4-2 shows the conversion of the population survivability curve to a survival probability curve by the least square fit method. The least square fit method choses the "best-fitting" curve to a set of data points that minimizes the sum of squares of the deviation of the data points from the predicted curve (Reference 3).

4.3 RESULTS USING THE POPULATION-WEIGHTED SURVIVABILITY OF PIECE PART FAMILIES TECHNIQUE

An example of the equipment survivability prediction technique based on 5ESS RHAP data is shown in Exhibits 4-3 and 4-4. The exhibits show the switch CDF and PDF survivability curves, respectively, generated from 26 piece part families determined by the K-S technique. The variances of the curves are very small, indicating that the prediction for the switch

EXHIBIT 4-3

CDF Survival Curves for the 5ESS Switch

(based on limited data and alternative method)

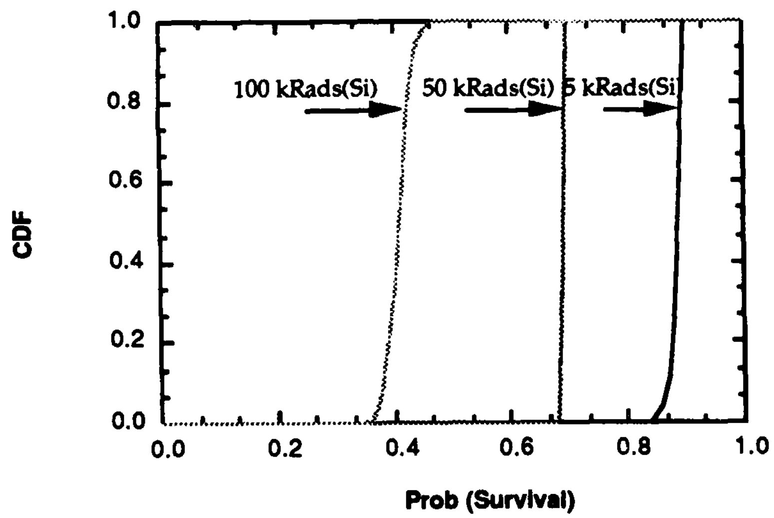
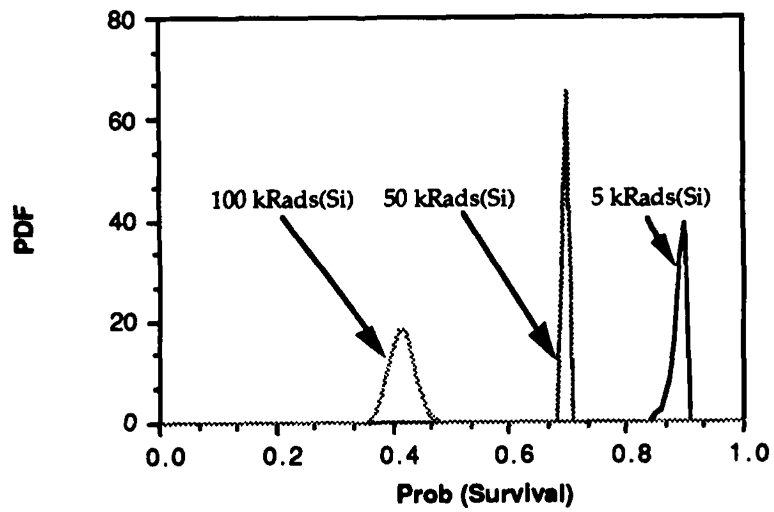


EXHIBIT 4-4

PDF Survival Curves for the 5ESS Switch

(based on limited data and alternative method)



survivability is tightly bound. The total number of piece parts in the 5ESS is assumed to be 1082. The survivability of the 5ESS switch is calculated for 5, 50, and 100 kRads(Si). These radiation levels are chosen to show a range of radiation response for the switch. At 5 kRads(Si), the curves indicate that the probability of survival for the 5ESS switch is about 90 percent. It is not until 100 kRads(Si) that the survivability of the 5ESS switch is reduced to roughly 40 percent.

4.4 DISCUSSION

Exhibits 4-3 and 4-4, which illustrate the results of the Population-Weighted Survivability of Piece Part Families technique, indicate that even at 100 kRads(Si) the survivability of the switch is about 40 percent. This is a very optimistic estimation of the switch survivability, because at this radiation level many of the critical devices in the 5ESS switch would have failed. Data from unhardened commercial equipment of similar complexity indicate many failures occurring well below 100 kRads(Si). The problem arises because the switch survivability curves are strongly dependent on the population of each piece part family. Therefore, although some piece part families fail at a low radiation dose level, they are not numerous enough in the switch to cause equipment failure. A significant number of piece parts must fail before there is a substantial decrease in the switch survivability. This indicates that basing the survivability of the switch on population alone may provide too optimistic a solution. If population is used as a weighting factor, it must be combined with other information about the equipment (e.g., percentage of mission critical piece parts).

The current technique's drawback is that it is insensitive to the number of piece parts in each family because switch survivability is based on piece part families. Therefore, switch survivability can only be affected by eliminating or adding piece part families.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This section describes conclusions regarding various techniques for quantifying equipment level Fallout Radiation effects based on the survivability of its piece parts. A series of three steps are employed to assess equipment level survivability. The steps are merging piece part data, quantifying piece part family survivability, and quantifying equipment survivability. Alternative techniques for each of the current techniques used are investigated. Recommendations for future activities are made to improve and expand the network level fallout radiation approach. These activities can further improve the existing methodology.

The K-S technique is the preferred technique for forming piece part families from individual piece parts. It provides a more statistically rigorous solution than the distribution-based technique. The K-S technique is one of many tests that can be performed on two data sets to determine if they are from the same distribution. The power of the test is it can be used on data without making assumptions about the data set (e.g. type of distribution, same mean, same standard deviation, etc.). There are some additions to the technique that can improve the confidence in the results. First, the K-S technique only looks for the maximum difference between the CDF curves, and does not evaluate the distribution of the differences. This distribution will provide more information about the likelihood of the occurrence of any particular value. In addition, the K-S technique is sensitive to the distribution of the two data sets. Data gaps over a small range may strongly affect the results by not allowing piece parts to be grouped.

The preferred technique for quantifying piece part family survivability is dependent on the results of the equipment level estimates of survivability. The current techniques for quantifying piece part family survivability (Bayesian technique) and equipment survivability (Survivability of All Piece Part Families technique) are always used together. The same is true of the alternative techniques used to predict these same survivabilities. The results given in Sections 4.4 and 4.5 indicate that using the Population-Weighted Survivability of Piece Part Families technique provides too optimistic a solution. Since the Weighted Binomial technique is used only with this

alternative technique for quantifying equipment survivability, it should not be used. Therefore, with the present information, the Bayesian technique is the preferred method for quantifying piece part family survivability.

The preferred technique for estimating equipment level survivability is the Survivability of All Piece Part Families technique. The switch survivability curves generated by the Population-Weighted Survivability of Piece Part Families may be optimistic. This is because the Population-Weighted Survivability of Piece Part Families approach assumes that the survivability of the equipment is dependent on the prevalence of piece part types. In telecommunications equipment, the survivability of the equipment should not be controlled by its strongest link. However, by using population as the sole criteria for survivability, the population of the strongest links in the equipment controls the survivability of the equipment. Although the alternative technique for predicting switch survivability is useful and produces reasonable results, it cannot be used as the sole criteria for survivability. Other parameters, such as the percentage of mission critical piece parts in the equipment, must be used in conjunction with the population factor to determine equipment survivability.

Given the present choices, the recommended overall equipment level fallout radiation approach is as follows:

- K-S technique to form piece part families from individual piece parts
- Bayesian technique to quantify piece part family survivability
- Survivability of All Piece Part Families technique to estimate equipment survivability.

The recommendations for improvements in the methodology are drawn from the conclusions of the analysis. The overall approach stated above is based on available information. However, the techniques not used may still be useful with the proper improvements. The suggested follow-on activities are:

- Increase the radiation data base on the device types used in the equipment. This will allow more families to be combined, and create greater confidence in the results of the K-S technique.

- Determine other weighting factors for the piece part family survivability curves. One area of investigation may be the sensitivity of the switch survivability to the percentage of mission critical piece parts in the equipment. The weighting factors will provide further insight to the response of the equipment to fallout radiation.
- Investigate improvements to the K-S test statistic. One area of investigation may be the distributions of the differences between two CDF curves. This can increase the confidence in the results from the K-S technique.

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APPENDIX A

This appendix describes, in mathematical detail, the approach to use population as a weighting factor for the survivability prediction of device families. The mathematics are included for anyone interested in the actual mechanics of the Weighted Binominal technique.

The general technique is described in Section 4.0. A combination of Bayesian statistics and Binomial distributions are use to generate the final device family survivability curve. Bayesian statistics use the radiation test data to predict the distribution of the probability of survival for a given family. Given a probability of survival and the number of piece parts in a family, the Binomial distribution can describe the probability that any number of piece parts will survive. However, in this case the Bayesian statistics generate a distribution of probabilities of survival, instead of just one. Therefore, a group of Binomial distributions can be generated using a different probability of survival for each distribution. The Binomial distributions generated can then be weighted by their probability of occurrence provided by the curve generated with the Bayesian statistics.

The following is a more mathematical description of the technique. The first step is to define the variables that are used in the equations.

Let j% = Probability of survival, which have a value anywhere from 0 to 1.

Let M = Number of values that j% can have, which will determine the fidelity of the survivability curves generated.

Let Y(j%) = Probability that j% is the survival probability (PDF Value), (generated using the raw radiation data and Bayesian Statistics.)

Let i = Number of piece parts that survive

Let N = Number of piece parts in the Piece Part Family

Let B(i,j%) = Probability that i number of piece parts survive, given j% is the probability of survival. This is just the value of a Binomial distribution for a given number of survivals and probability of surivival.

B(i,j%) can then be expressed as the following:

$$\text{For any } j\%,\ B(i,j\%) = \frac{N!}{(i)!(N-i)!}(j\%)^{i}(1-j\%)^{(N-i)} \qquad \text{(A-1)}$$

The two special cases when Equation A-1 is not valid are as follows:

If j% = 0, Then B(0,0) = 1 and All Other B(i,0) = 0 (A-2)

If j% = 1, Then B(N,1) = 1 and All Other B(i,1) = 0 (A-3)

The above equations define the Binomial distribution for each probability of survival value chosen. However, it does not describe the likelihood that each Binominal distribution curve will occur. This is described by the distribtuion generated by the Bayesian statistics.

The survivability curve for the piece part family is then defined by the following:

$$P(i) = \sum_{k=1}^{M} Y(j_k\%)B(i,j_k\%)$$

APPENDIX B

This appendix describes, in mathematical detail, the approach to predict the switch survivability. The mathematics are included for anyone interested in the actual mechanics of the Population-Weighted Survivability of Piece Part Families Technique.

The general technique is described in Section 5.0. The two tasks to be performed are the the convolution of the device family survival curves and the change in the random variable described in the switch survivability curve.

The convolution is performed using the Fast Fourier Transform (FFT). No attempt is made to describe the actual mathematics of a FFT, but a description can be found in Reference 7. The FFT is a method to perform the Fourier Analysis on real, discrete data. The FFT transforms data into the transformed domain, and the Inverse FFT (IFFT) transforms the data back to the original domain. FFT is used because convolution in one domain of the Fourier Analysis is just multiplication in the other domain. Each piece part family survivability curve is transformed into the new domain. The data for each piece part family is then multiplied in this new domain. The resulting product is the switch survivability curve in the transformed domain. The IFFT is used to convert the switch survivability curve back to the original domain. The resulting survivability curve describes the probability that any given number of piece part survive in the switch.

The survivability curve must then be expressed in a distribution of the probability of survival, instead of a distribution of the number of piece parts that survive. This is done by using the Sum of Least Squares fit technique, which generates a curve that is the best fit for the given data. The concept behind this technique is that if a set of data is assumed to fit a specific type of curve, the data can be used to find the correct variables for the specified curve. This is done by minimizing the error between the given data and the curve of interest. If the data fits the curve perfectly, the error is zero. However, in general, only the best fit curve to the data is obtained.

Using the definition given in Appendix A and defining M = 101, j% will be incremented by 0.01, and Equation A-1 is redefined as:

$$Y(i) = \sum_{j=0}^{100} P(j\%)B(i,j\%) \tag{B-1}$$

The right side of the Equation B-1 is the curve to which the data is to be fitted. The data set that is generated by the convolution can be defined as D(i). Therefore, using the Sum of Least Squares fit, the error is defined as:

$$E = \sum_{i=0}^{N} \left\{D(i) - \sum_{j=0}^{100} P(j\%)B(i,j\%)\right\}^2 \tag{B-2}$$

The object of the technique is to chose the parameters of the curve to minimize the error. This is done by first taking the derivative of the error with respect to the parameter of interest, which is the probability of survival (j%). The derviative is given by the following:

$$\frac{dE}{dP(k\%)} = \sum_{i=0}^{N} \left[2\left\{D(i) - \sum_{j=0}^{100} P(j\%)B(i,j\%)\right\}\left\{-B(i,k\%)\right\}\right]$$

To minimize the error, the derivative is set to zero:

$$0 = \sum_{i=0}^{N} \left[\left\{D(i) - \sum_{j=0}^{100} P(j\%)B(i,j\%)\right\}\left\{B(i,k\%)\right\}\right]$$

The following mathematical manipulations isolate the variable of interest and its distribution, P(j%).

$$\sum_{i=0}^{N} Y(i)B(i,k\%) = \sum_{i=0}^{N} B(i,k\%) \sum_{j=0}^{100} P(j\%)B(i,J\%)$$

Therefore:

$$\sum_{i=0}^{N} Y(i)B(i,k\%) = \sum_{j=0}^{100} P(j\%) \sum_{i=0}^{N} B(i,k\%)B(i,j\%)$$

where K = 0,1,2, ..., 100

This equation can be expanded in a matrix format to solve for P(j%), which is the distribution of the survival probabilities for the switch. Since Y(i) and B(i,j%) are known from the convolution of the device families, P(i), the distribution of the probability of survival for the switch, can be solved using matrix techniques. No attempt is made to describe the actual mathematics associated with matrix manipulations in the field of linear algebra, but a description can be found in Reference 8.

$$
\begin{bmatrix}
\sum_{i=0}^{N} Y(i)B(i,0) \\
\sum_{i=0}^{N} Y(i)B(i,.01) \\
\vdots \\
\sum_{i=0}^{N} Y(i)B(i,.99) \\
\sum_{i=0}^{N} Y(i)B(i,1)
\end{bmatrix}
=
\begin{bmatrix}
\sum_{i=0}^{N} B(i,0)B(i,0) & \cdots & \sum_{i=0}^{N} B(i,1)B(i,0) \\
\sum_{i=0}^{N} B(i,0)B(i,.01) & \cdots & \sum_{i=0}^{N} B(i,1)B(i,.01) \\
\vdots & & \\
\sum_{i=0}^{N} B(i,0)B(i,.99) & \cdots & \sum_{i=0}^{N} B(i,1)B(i,.99) \\
\sum_{i=0}^{N} B(i,0)B(i,1) & \cdots & \sum_{i=0}^{N} B(i,1)B(i,1)
\end{bmatrix}
\begin{bmatrix}
P(0) \\
P(.01) \\
\vdots \\
P(.99) \\
P(1)
\end{bmatrix}
$$